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MAGNETIC RESONANCE DEVICE COMPRISING AN EDDY-CURRENT GENERATOR

The invention concerns a magnetic resonance apparatus.

Magnetic resonance technology is a known technology to, among other things, acquire images of the inside of a body of an examination subject. For this, in a magnetic resonance apparatus rapidly switched gradient fields that are generated by a gradient coil system are superimposed on a static basic magnetic field that is generated by a basic field magnet. The magnetic resonance apparatus also comprises a radio-frequency system that radiates radio-frequency signals into the examination subject in order to resolve magnetic resonance signals and acquires the generated magnetic resonance signals on the basis of which magnetic resonance images are created.

A superconducting basic field magnet comprises, for example, an essentially hollow-cylindrical helium reservoir in which superconducting coils are arranged that are cooled by the fluid helium surrounding them. The helium reservoir is enclosed by a hollow-cylindrical inner cryoshield that is in turn enclosed by a hollow-cylindrical outer cryoshield. For this, the cryoshields are fashioned from a metal with good heat conductivity, for example aluminum. The cryoshields and/or the helium reservoir are thereby kept at predeterminable temperatures via cryo-coolers, cold gas or liquid nitrogen. The outer cryoshield is ultimately enclosed by an essentially hollow-cylindrical vacuum reservoir. The reservoirs are thereby normally fashioned from non-magnetic stainless steel. The helium reservoir is connected with the inner cryoshield, both cryoshields are interconnected, and the outer cryoshield is connected with the vacuum reservoir, all of them in a poorly heat-conductive manner at a mutual separation of a few millimeters up to a few centimeters.

A hollow-cylindrical gradient coil system is attached in the cylindrical hollow of the vacuum reservoir, for example via wedging into the hollow. To generate gradient fields, corresponding currents are adjusted in the gradient coil. The amplitudes of the required currents thereby amount to more than 100 A. The current rise and fall rates amount to more than 100 kA/s. An existing basic magnetic field affects these temporally changing currents in the gradient coil on the order of 1 T Lorentz forces, which lead to oscillations of the gradient coil system and therewith to unwanted acoustic noises and image quality interferences.

For example, in DE 44 32 747 A1 a reduction in principle of oscillations of the gradient coil system via an active measure is specified. For this, an apparatus, in particular comprising electrostrictive elements, is arranged in or on the gradient coil system. With this apparatus, forces can be generated that counteract the oscillations of the gradient coil system, such that a deformation of the gradient coil system is substantially prevented. The electrostrictive elements are correspondingly controlled for this via an electrical voltage applied to them.

The gradient coil system is normally surrounded by conductive structures in which eddy currents are induced via the switched gradient fields. Examples for such conductive structures are the vacuum reservoir and/or the cryoshields of the superconducting basic field magnet, a radio-frequency shield, for example made from a copper foil, and an antenna of the radio-frequency system. The fields as a consequence of the eddy currents are unwanted because without countermeasures they weaken the gradient fields and distort them in their time curve, which leads to impairment of the quality of magnetic resonance images.

The distortion of a gradient field as a result of the eddy current fields can be compensated up to a certain degree by a corresponding predistortion of a quantity controlling the gradient field. To compensate, the controlling quantity is thereby to be filtered such that eddy current fields ensuing given non-predistorted operation of the gradient coil are cancelled out by the predistortion. A filter network can be

used for filtering whose parameters are determined by the time constants and coefficients that can, for example, be determined with a method corresponding to DE 198 59 501 C1.

Via a use of an actively shielded gradient coil system, the eddy currents induced by the gradient coils fed with current (said eddy currents on a predeterminable enveloping surface that, for example, runs through the inner cylinder jacket of the 80 K cryoshield of the superconducting basic field magnet) can also be reduced.

Furthermore, a radio-frequency shield provided with dividing slits is, for example, known from DE 198 43 905 A1 for a magnetic resonance apparatus, whereby the radio-frequency shield is, among other things, slitted such that the eddy currents induced by the gradient fields in the radio-frequency shield are optimally suppressed.

It is an object of the invention to achieve an improved magnetic resonance apparatus in which, among other things, unwanted eddy current effects are better controlled.

The object is achieved via the subject matter of the claim 1. Advantageous embodiments are specified in the sub-claims.

According to claim 1, in a magnetic resonance apparatus with

- a basic field magnet to generate a basic magnetic field,
- at least one eddy current generator, and
- at least one electrically-conductive structure in which eddy currents can be caused by the eddy current generator, such that Lorentz forces act on the structure in the basic magnetic field,

attached to the structure is a force generator that is fashioned and can be controlled such that forces counteracting the Lorentz forces can be generated with the force generator, such that a movement and deformation of the structure is prevented.

The invention thereby emanates from the following realization: via the switched gradient fields, eddy currents are induced in a conductive structure on which eddy currents, for their part, Lorentz forces act in the basic magnetic field such that the conductive structure is also excited to oscillations, which leads to induction of further eddy currents and therewith as a consequence to further oscillations, and so forth. However, as soon as the conductive structure Device [sic] into oscillations, a damping of these oscillations is only possible via a sophisticated sensor-actuator combination, since these oscillations depend on a resonance behavior of the conductive structure and are determined by the further eddy currents. According to the invention, aforementioned complexity is prevented in that a force generator is attached to the conductive structure, said force generator being fashioned such that it generates forces that counteract those forces that act on the eddy currents generated by the gradient fields in the conductive structure. A movement and/or oscillation of the conductive structure is therewith prevented from the outset. It is thereby of advantage that the gradient fields are spatially constant and can be scaled directly with currents of the individual gradient axes flowing in the gradient coils, such that the eddy currents thereby excited run on exact predictable paths or paths to be measured once that, as the case may be, exhibit optimally different decay curves. This also opens up the possibility of a simple control of the force generator based on a temporal current curve in the gradient coils, whereby in particular a portion of the eddy current-compensating predistortion corresponds to a portion and time curve of the eddy currents.

Further advantages, features and details of the invention result from subsequent specification of exemplary embodiments of the invention using the drawing [sic]. Thereby shown are:

Figure 1 a longitudinal section through a magnetic resonance apparatus with a gradient coil system and a force generator,

Figure 2 per section, a detailed longitudinal section through the force generator in a first embodiment,

Figure 3 per section, a detailed longitudinal section through the force generator in a second embodiment,

Figure 4 a perspective view of the gradient coil system with four annular coils to detect magnetic fields of the gradient coil system, and

Figure 5 per section, a perspective view of the gradient coil system with a area-covering arrangement of annular coils.

As an exemplary embodiment of the invention, Figure 1 shows a longitudinal section through a magnetic resonance apparatus. The magnetic resonance apparatus thereby comprises an essentially hollow-cylindrical basic field magnet 100 with which, at least within an imaging volume 150 of the magnetic resonance apparatus, an optimally homogenous static basic magnetic field can be generated. The basic field magnet 100 comprises an essentially hollow-cylindrical helium reservoir 100 made of non-magnetic stainless steel, in which superconducting solenoid coils 113 are arranged on a winding carrier, said solenoid coils 113 being cooled to 4.2 K by the liquid helium surrounding them.

The helium reservoir 110 is enclosed by a hollow-cylindrical 20 K cryoshield 120 that is in turn enclosed by a hollow-cylindrical 80 K cryoshield 130. The cryoshields 120 and 130 thereby effect that optimally little radiant heat penetrates to the helium reservoir 110 from the outside and are fashioned from a metal with good heat conductivity. Via cry-coolers, cold gas or liquid nitrogen, the 20 K cryoshield is kept at a temperature of 20 K and the 80 K cryoshield is kept at a temperature of 80 K.

The 80 K cryoshield is ultimately enclosed by an essentially hollow-cylindrical vacuum reservoir 140 made from non-magnetic stainless steel. The helium reservoir 110 is thereby connected with the 20 K cryoshield 120, both cryoshields 120 and 130 are interconnected, and the 80 K cryoshield 130 is connected with the vacuum reservoir 140, all of them in a poorly heat-conductive manner at a mutual separation of a few millimeters up to a few centimeters, for example via thin fiberglass rods.

The magnetic resonance apparatus also compries [sic] a gradient coil system 200 that comprises gradient coils and associated shielding coils and with which a gradient control unit 250 is associated. The essentially hollow-cylindrical gradient coil system 200 is thereby attached in the cylindrical hollow of the vacuum reservoir 140 via wedging.

To control the currents in the coils, the gradient coil system 200 is connected with the gradient control unit 250. Within the imaging volume 150, rapidly switched magnetic gradient fields can be superimposed on the basic magnetic field with the gradient coil system 200 fed with current.

The gradient coil system 200 thereby comprises, from the inside out, the following hollow-cylindrical regions 210 through 245 that are arranged concentrically relative to one another: a first hollow-cylindrical region 210 comprises an x-gradient coil to generate an x-gradient field with a gradient collinear to the x-axis of a Cartesian coordinate system. A second hollow-cylindrical region 220 comprises a y-gradient coil to generate a y-gradient field with a gradient collinear to the y-axis. The x- and y-gradient coils thereby comprise four partial coils fashioned saddle-shaped. A third hollow-cylindrical region 240 comprises a cooling device to, among other things, cool the gradient coils. A fourth hollow-cylindrical region 230 comprises a z-gradient coil to generate a z-gradient field with a gradient collinear to the z-axis, whereby the z-gradient coil comprises, for example, two solenoid partial coils.

A fifth hollow-cylindrical region 245 comprises active and/or passive shim devices and a further cooling device. A z-shielding coil associated with the z-gradient coil is arranged in a sixth hollow-cylindrical region 235. A seventh hollow-cylindrical region 215 comprises an x-shielding coil that is associated with the x-gradient coil. Finally, an eighth hollow-cylindrical region 225 comprises a y-shielding coil that is associated with the y-gradient coil.

The shielding coils associated with the gradient coils are thereby fashioned and can be supplied with current such that the magnetic fields that can be generated with the shielding coils compensate the magnetic fields that can be generated with the associated gradient coils on the inner cylinder jacket of the 80 K cryoshield 130, at least such that fewer eddy currents are induced in the inner cylinder jacket by the gradient coil system 200 fed with current relative to a gradient coil system without shielding coils.

So that the switched gradient fields in the imaging volume 150 are not distorted by eddy current induction and eddy current magnetic fields as a consequence thereof, the gradient control unit 250 operates with correspondingly predistorted control quantities for the currents of the gradient coils and associated shielding coils. For this, the gradient control unit 250 comprises a corresponding predistortion unit 260 that comprises a separate predistortion unit 261, 262 and 263 for each of the three gradient axes x, y and z.

Furthermore, to radiate radio-frequency signals into an examination subject positioned in the imaging volume 150, as well as to acquire magnetic resonance signals from the examination subject, the magnetic resonance apparatus comprises an antenna 310. A radio-frequency shield 320 is thereby arranged between the antenna 310 and the gradient coil system 200 to shield from outer interfering influences.

Furthermore, the magnetic resonance apparatus comprises a force generator 400 that, as a hollow cylinder of small wall thickness, is attached like a layer to the inner cylinder jacket of the vacuum reservoir 140. Via the switched gradient fields, in the inner cylinder jacket of the vacuum reservoir 140 eddy currents are induced on which Lorentz forces act in the basic magnetic field, such that (without countermeasures) a deformation, movement and/or oscillation of the inner cylinder jacket would be the result. The force generator 400 is thereby fashioned and can be controlled such that the force generator 400 can generate forces counteracting the aforementioned Lorentz forces, such that the deformation, movement and/or oscillation of the inner cylinder jacket is prevented. For a corresponding control of the force generator 400, a force generator control unit 490 is associated with the force generator 400, said force generator control unit 490 being linked with the gradient control unit 250, in particular its predistortion unit 260. The predistortion of the coil currents can thereby be used to control the force generator 400, since the predistortion mirrors the precise portion and the time curve of the eddy currents.

As an exemplary embodiment of the invention, Figure 2 shows in sections a detailed longitudinal section through the force generator 400 in a first embodiment. The force generator 400 thereby comprises three layers 410, 420 and 430 in which electrostrictive fibers 475 or whole bundles of such fibers are arranged. The electrostrictive fibers 475 are thereby arranged in the layer 430 corresponding to a spatial distribution of the Lorentz forces (that are caused by the z-coils fed with current) acting upon the inner cylinder jacket of the vacuum reservoir 140. However, in the layers 420 and 410 the electrostrictive fibers 475 are arranged corresponding to the Lorentz forces caused by the x- and y-coils fed with current. A very fine spatial resolution can thereby achieved with advantage with the electrostrictive fibers 475.

In other embodiments, instead of the fibers 475, electrostrictive elements that are fashioned foil-like, plate-like and/or stack-like can also be used, as well as magnetostrictive and/or hydraulic force generators.

The electrostrictive fibers 475 are thereby respectively arranged per layer 410, 420 and 430 between two contacting layers 415 and 416, 425 and 426 and 435 and 436. Electrically-insulating layers 440 and 445 are arranged between the contacting layers 426 and 415 as well as 416 and 425. Between the contacting layers 415 and 416, 425 and 426 and 435 and 436, electrical voltages can be applied that effect a striction of the electrostrictive fibers 475 and therewith a force perpendicular to the surface of the inner cylinder jacket of the vacuum reservoir 140.

The electrical voltages are thereby provided by the force generator control unit 490, whereby the layer 420 is controlled by the predistortion unit 262 corresponding to a predistortion for the y-coils, the layer 410 is controlled by the predistortion unit 261 corresponding to a predistortion for the x-coils, and the layer 430 is controlled by the predistortion unit 263 corresponding to a predistortion for the z-coils.

As a further exemplary embodiment of the invention, Figure 3 shows in sections a detailed longitudinal section through the force generator 400 in a second embodiment. Electrostrictive fibers 475 are thereby arranged uniformly distributed in a layer 450. The layer 450 is thereby arranged between two contacting layers 455 and 456, whereby both contacting layers 455 and 456 are divided in a congruent manner into partial contactings. The partial contactings are insulated from one another and are arranged covering the layer 450 like a parquet. Two partial contactings that are respectively opposite one another relative to the layer 450 thereby form a pair. With the force generator control unit 490, an electrical voltages [sic] can thereby be applied to each one of the pair, whereby for each one of the pair the voltage can be adjusted independent of the voltages on other pairs. In the layer 450, corresponding regions of one or more of the electrostrictive fibers 475 can therewith be controlled independent of one another and with different strictions.

Relative to the first embodiment, the layer thickness of the force generator 400 is reduced with advantage; for this, the many partial contactings are to be controlled separately and normally with different voltages. For an equally effective control as in the first embodiment, the predistortions of the individual predistortion units 261, 262, 263 can thereby not be used directly, but rather are first to be further processed in the force generator control unit 490 and transferred to the individual partial contactings. For the further processing, in principle the Lorentz force spatial distributions that each of the coils causes on the inner cylinder jacket of the vacuum reservoir 140 are thereby to be determined, for example via measuring, and to be stored in the force generator control unit 490. Furthermore, in the second embodiment, due to the many partial contactings, spatially different decay times of eddy currents that predominate in different regions of the inner cylinder jacket are accommodated by a corresponding control.

In other embodiments, the first and the second embodiment are combined with one another. Thus, for example, aforementioned different decay times in the first embodiment are accommodated, in that the contacting layers 415, 416, 425, 426, 435 and 436 are also divided into at least a few partial contactings.

The additional weight of the force generator 400 does not change the Lorentz forces occurring in the inner cylinder jacket of the vacuum reservoir 140, and the thin, conductive contacting layers 415, 416, 425, 426, 435, 436, 455 and 456 of the force generator 400, that for their part represent a conductive structure for eddy current induction, at most change an amplitude of the Lorentz forces to be compensated on the inner cylinder jacket.

For a fine tuning in the force generator control unit 490, in addition to the stored information and the information from the predistortion unit 260, the magnetic fields generated by the individual gradient coils and associated shielding coils and causing eddy currents can also be at least selectively measured and supplied to the force generator control unit 490 as a scaling quantity. It is thereby sufficient to

record only the radially directed components of the magnetic fields, since only these cause eddy currents. Of these thusly excited eddy currents, only the currents in the circumferential direction are thereby significant, since the Lorentz forces in the radial direction act only on these, which (without the countermeasure of the force generator 400) would lead to oscillations of the vacuum reservoir 140, and thus noise and further secondary eddy currents would be caused.

Figure 4 shows a perspective view of the gradient coil system 200 with four annular coils 511, 512, 521 and 522 attached to the gradient coil system 200, whereby the annular coils 511, 512, 521 and 522 are identically positioned relative to the z-direction, the annular coils 511 and 512 are arranged in a y-z plane, and the other annular coils 521 and 522 are arranged in an x-z plane.

The annular coils 511 and 512 are thereby arranged in a region of the gradient coil system 200 in which, due to their symmetry properties independent of their operating state, the y-coils produce radially-directed magnetic field components. The annular coils 521 and 522 are arranged in a corresponding region of the x-coils. The four annular coils 511, 512, 521 and 522 can be sufficiently separated from one another in order to detect the radially-directed magnetic field components of the gradient coils and associated shielding coils corresponding to the individual axes x, y and z. Thus, for example, an equally large signal on all annular coils 511, 512, 521 and 522 means that only the z-coils produce a radially-directed magnetic field component. In contrast to this, if the signals of both of the annular coils 511 and 512 are different, this thus means that the difference falls on a radially-directed magnetic field component of the x-coils. A difference between the signals of the two annular coils 521 and 522 thereby characterizes a contribution from the y-coils.

As a further exemplary embodiment of the invention, Figure 5 shows an area-covering arrangement of annular coils 510 on the surface of the gradient coil system 200. Each of the annular coils 510 is thereby, for example, arranged

corresponding to a partial contacting of Figure 3 and is respectively associated with one of the partial contactings. Similar to the annular coils 511, 512, 521 and 522 of Figure 5, the annular coils 510 are thereby fashioned only to acquire radially-directed magnetic field components. The respectively associated partial contacting can be controlled with the measurement signal of each one of the annular coils 510. A control on the basis of the predistortion, and likewise a separation of the magnetic field components with regard to the axes x, y and z, can therewith be foregone.

In other embodiments, instead of annular coils other sensors can thereby be used that are sensitive to the magnetic fields generated by the gradient coils and associated shielding coils and in particular not sensitive to vibrations, for example Hall probes.

In a likewise different embodiment, the eddy currents occurring in the cylinder jacket of the vacuum reservoir or in the contacting layers 455 or 456 are detected directly and are used to control the force generator 400 in the second embodiment according to Figure 3. Since the eddy currents are thereby detected exclusively, and the magnetic fields of the gradient coils and associated shielding coils should not be detected as well, the eddy currents can, for example, be detected based on their thermal effect, whereby the detection results are to be transduced into corresponding electrical voltages for the partial contactings.